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14. ABSTRACT <p>Research was conducted to develop advanced laser-based diagnostics for non-intrusive measurements relevant to air-breathing combustion. The program emphasized the use of spectrally-resolved absorption with cw tunable diode lasers (TDL) and the use of planar laser-induced fluorescence (PLIF) with pulsed IR and UV laser sources. Progress during the past year was highlighted by results in five areas including: 1) progress on understanding the photophysics of toluene to enable its use as a PLIF indicator of fuel-air ratio, 2) development and demonstration of new schemes for quantitative LIF of NO at high pressure, 3) observation of the first UV PLIF images of carbon dioxide, 3) fundamental measurements of IR PLIF for species with inaccessible electronic transitions, 4) investigation of 2f wavelength-modulation techniques for temperature measurement in high-pressure and/or high-temperature gas flows, and 5) temperature measurements via optical absorption in the UV and NIR spectral regions targeting CO₂ and H₂O, respectively.</p>					
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Annual Technical Report

LASER DIAGNOSTICS FOR REACTING FLOWS

Grant AFOSR FA9550-04-0009

Prepared for

Air Force Office of Scientific Research

Dr. Julian Tishkoff, Technical Monitor

For the Period

August 1, 2004 to July 31, 2005

Submitted by

Professor Ronald K. Hanson, Principal Investigator

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.2.0 Objectives:

The goal of this project is to establish advanced laser-based techniques for non-intrusive measurements relevant to air-breathing propulsion. Separate but complementary topics are included, all of which are based on fluorescence or absorption spectroscopies. The first of these topics addresses fundamental photophysics of flow tracers for PLIF imaging, with the objective of identifying improved tracers for fuel mixing, temperature, and pressure. The second topic focuses on diagnostics of combustion product gases at high temperature and pressure. The UV absorption of hot CO₂ discovered during the previous grant is exploited here to demonstrate the potential for gas temperature diagnostics and to investigate the potential of UV LIF from CO₂. The third topic continues our innovative pioneering efforts to develop planar laser-induced fluorescence (PLIF) imaging techniques for infrared transitions. These infrared techniques enable the imaging of important combustion species, particularly hydrocarbon fuels and combustion products, which are not amenable to detection with present PLIF schemes operating at UV and visible wavelengths. The fourth topic continues our development of multiplexed laser sensors with emphasis on diagnostics for two-phase fuel sensing and temperature measurement in high-temperature and high-pressure combustion product gases.

3.0 Status of Effort:

Research was conducted to develop advanced laser-based diagnostics for non-intrusive measurements relevant to air-breathing combustion. The program emphasized the use of spectrally-resolved absorption with cw tunable diode lasers (TDL) and the use of planar laser-induced fluorescence (PLIF) with pulsed IR and UV laser sources. Progress during the past year was highlighted by results in five areas including: 1) progress on understanding the photophysics of toluene to enable its use as a PLIF indicator of fuel-air ratio, 2) development and demonstration of new schemes for quantitative LIF of NO at high pressure, 3) observation of the first UV PLIF images of carbon dioxide, 3) fundamental measurements of IR PLIF for species with inaccessible electronic transitions, 4) investigation of 2f wavelength-modulation techniques for temperature measurement in high-pressure and/or high-temperature gas flows, and 5) temperature measurements via optical absorption in the UV and NIR spectral regions targeting CO₂ and H₂O, respectively.

4.0 Accomplishments/New Findings:

4.1 Tracer Photophysics for Quantitative PLIF Diagnostics

Ongoing photophysical studies of ketone and aromatic tracers continue to yield insight and new strategies for quantitative PLIF diagnostics of temperature and concentration in flows relevant to combustion. Our recent work suggests that toluene, an aromatic compound that comprises a significant fraction of JP-8 and hydrocarbon fuels, has good potential for high-resolution temperature imaging [1-5]. Like the ketones we have studied previously, toluene's attractive characteristics are recognizable – a realistic fuel with accessible electronic transitions and strong red-shifted fluorescence signals. Realization of robust, quantitative diagnostic tools over a range of temperatures, however, requires fundamental understanding of the fluorescence behavior. Figure 1 shows toluene's relative fluorescence signal as a function of temperature at a total pressure of 1 bar, revealing extremely large temperature sensitivity especially for 248-nm excitation. Since toluene signals are much larger than ketone signals at room temperature, toluene imaging has the potential for unprecedented temperature resolution. Work is currently underway to investigate and demonstrate this possibility in more detail.

4.2 Wavelength-Resolved NO-LIF in High-Pressure Flames

PLIF imaging is a useful diagnostic for spatially resolved temperature and species concentrations in practical systems. NO is an attractive target species for PLIF because it naturally occurs in air-breathing combustion, can be easily seeded into test facilities, and has a strong LIF signal. However, quantitative laser-induced fluorescence (LIF) measurements of NO in high-pressure flames are complicated by interference LIF from O_2 and CO_2 . Understanding these interferences has been an important research topic in recent years. During this past year, we have utilized wavelength-resolved fluorescence as a means of quantifying the contribution of interference signal from various species (e.g., LIF from hot O_2 and CO_2) when detecting NO-LIF in high-pressure flames, and have incorporated this understanding into a wavelength-scanned temperature-fitting technique [6]. Simulation models have been developed for each of the relevant species. Work is currently underway to use wavelength-resolved LIF emission as a practical method of imaging NO-LIF for quantitative concentration measurements and for thermometry in high-pressure flames.

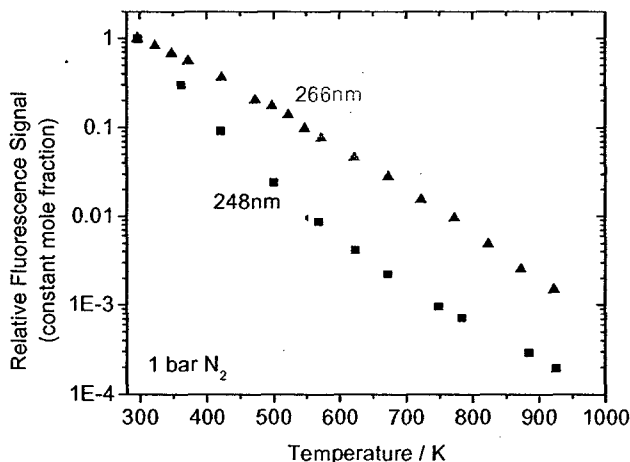


Figure 1. Relative toluene LIF signal from 248-nm and 266-nm excitation as a function of temperature at 1 bar total pressure (diluted with nitrogen). High signals at room temperature and strong temperature sensitivity indicate the potential for high-resolution temperature field measurements using toluene as a tracer.

4.3 IR PLIF using Vibrational Transitions

Molecules such as CO, CO_2 , H_2O , and hydrocarbon fuels are extremely important in combustion processes, yet difficult to image. In particular, these molecules are not easily accessible using single-photon UV/visible PLIF. However, single-photon infrared excitation of these species and collection of the subsequent vibrational fluorescence is possible. Detailed knowledge of energy transfer processes is needed in order to design PLIF strategies and interpret IR PLIF data. Because of these needs, much of our current work is focused on developing and experimentally verifying energy transfer models for mixtures of combustion gases (CO , CO_2 , H_2O , N_2 , O_2 , H_2). In addition to the modeling efforts, challenges that need to be addressed for application of IR PLIF to harsh combustion environments are being studied, and strategies to overcome these challenges are being developed. Finally, development of simplified IR-laser systems for the excitation of CO, CO_2 , and unburnt hydrocarbon LIF is underway.

4.4 Near-IR Diode Laser-Based Wavelength-Modulated Absorption for High-Pressure Flows

Absorption spectroscopy becomes challenging in high-pressure flows as collision broadening blends the transitions and renders it impossible to tune "off-resonance" to determine the baseline needed for quantitative measurements (e.g., see figure 2a). Wavelength-modulation-absorption spectroscopy (WMS) with second-harmonic ($2f$) detection, conducted with near-IR lasers, provides a promising strategy for measuring temperature and species concentration under these conditions[7], but the broad and blended absorption features require large wavelength-modulation depth to maximize the $2f$ signal. It has been recognized that large wavelength modulation is accompanied by a modulation of laser intensity, and recent $2f$ simulations have

included this intensity modulation (IM). However, in a real diode laser, this IM becomes nonlinear and there is a phase shift between the frequency modulation and the intensity modulation (FM/IM phase shift). These effects are enhanced at large modulation depth. Accordingly during the past year, FM/IM phase shift and non-linear IM effects have been incorporated into the Stanford $2f$ -model resulting in substantially improved agreement between simulation and measurement for high-pressure applications, as shown in Fig. 2b (see Ref 8 for details). The improved model has uncovered a new strategy for normalizing the $2f$ signal-magnitude with the $1f$ signal-magnitude, thereby removing the need for calibration of the $2f$ diagnostic. This is a major simplification of $2f$ WMS absorption spectroscopy. Successful measurements to test these principles are being conducted in a high-pressure shock tube.

4.5 Temperature Measurements via UV CO_2 and Near-IR H_2O Absorption

Accurate knowledge of temperature and pressure in shock tube experiments is critical for quantitative evaluation of ignition times and chemical reaction rates. New combustor concepts require such data at lower temperatures and longer reaction times than is currently feasible using the normal assumption of constant temperature and pressure behind reflected shock waves. The development and use of a sensitive and accurate scheme for monitoring the actual temperature time-history therefore could increase dramatically the useful test time of shock tubes. We believe that laser diagnostics based on CO_2 and H_2O absorption have the potential to provide this critical information.

Earlier in this program, we discovered that CO_2 absorption cross-sections become significant between 205nm and 320nm at temperatures above 1000K. This absorption allows for thermometry in combustion systems because the shape of the CO_2 UV absorption spectrum varies strongly with temperature [9]. During the past year the CO_2 absorption cross-section was measured precisely using cw lasers at 216.5, 244, 266, and 306 nm for $1500 < T < 4500\text{K}$ [10]. With this data, UV absorption was used for microsecond time-resolved temperature measurements behind shock waves in both non-reacting and reacting (methane ignition) systems. The non-reacting experiments show excellent agreement with temperature results derived from an isentropic assumption and a pressure measurement [11]. For systems with significant heat release, the temperature increase differs from that predicted using a constant-volume assumption (see Fig. 3), confirming the importance of direct temperature measurements.

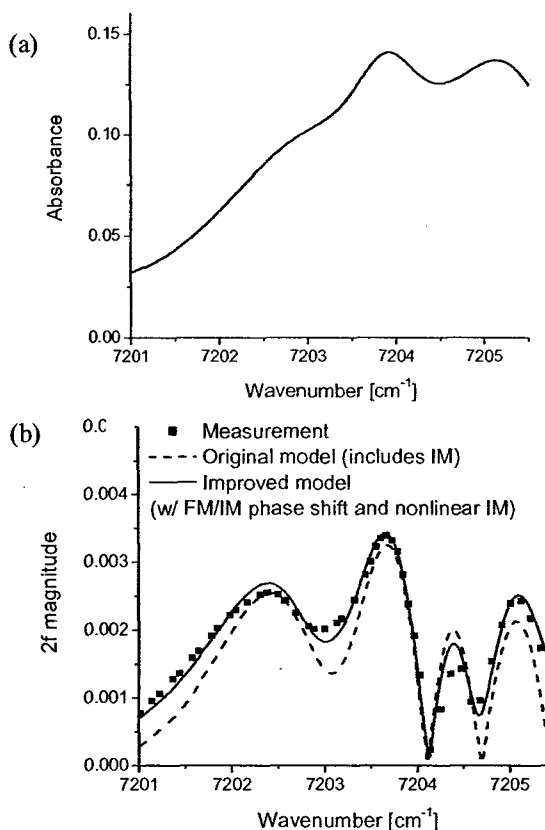


Figure 2. (a) Simulated H_2O direct absorption spectrum for $P=10$ bar, $T=296\text{K}$, 0.16% H_2O , 100.5cm path length (b) Measured and simulated $2f$ spectra for the same conditions with a modulation depth 0.65 cm^{-1} and modulation frequency 50 kHz.

Time-resolved temperature data will allow extension of shock-tube test time into periods influenced by non-ideal behavior, e.g. following reflected shock interactions with the contact surface. This will enable the use of a shock tube to determine low-temperature ignition times needed for modern, low-emissions aero-engines. A sensor based on wavelength-multiplexed NIR absorption of water vapor has been developed for this purpose. Initial results in well-characterized heated cell and shock tube gases confirm the potential for highly accurate temperature measurements.

4.6 Wavelength-Multiplexed TDL Sensing for a Scramjet Combustor

A wavelength-multiplexed tunable diode laser (TDL) sensor was developed for measurements of gas temperature and water concentration in a scramjet combustor. Initial measurements were performed in 2002 at the Air Force Research Laboratory, and following a re-design of the sensor, a return trip to AFRL in 2004 yielded a factor of 35 improvement in SNR as illustrated in Fig 4 [12]. The sensor is comprised of three fiber-coupled TDLs

which are wavelength-scanned at kilohertz rates across water vapor spectral features; single-scan samples from both measurement campaigns are shown in Fig. 4 for two of the lasers. The primary noise sources encountered during the first campaign were beam-steering as the light passed through the supersonic flow and mode noise from the multi-mode fiber transporting the light from the combustor to the detectors. Optical engineering studies thus focused on minimizing these two effects. The improved SNR allows more accurate determination of the integrated absorbance of each feature, which is used to infer temperature and water concentration. In addition, the SNR improvement allows measurements at rates fast enough to identify characteristic fluctuation frequencies in the exhaust gases (unsteady pattern factors).

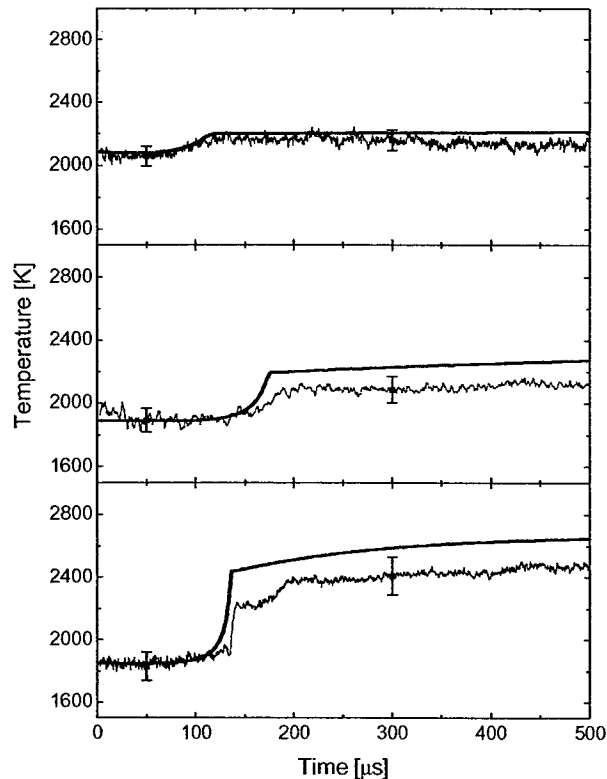


Figure 3. Measured temperature (solid thick lines) versus constant volume calculation (solid thin lines) in reflected shock wave methane ignition experiment. Top graph (initial reflected shock conditions): 1% CH₄/ 2% O₂/ 10% CO₂/ Ar, 2085 K, and 0.128 MPa. Middle graph: 2% CH₄/ 4% O₂/ 10% CO₂/ Ar, 1890 K, 0.134 MPa. Bottom graph: 4% CH₄/ 8% O₂/ 10% CO₂/ Ar, 1851 K, 0.126 MPa. Post-shock vibrational equilibrium was assumed. Error bars represent a 1- σ confidence interval.

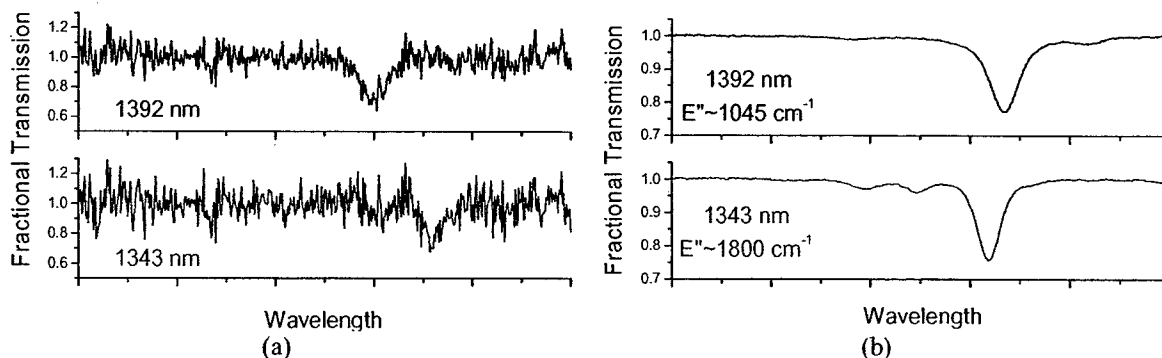


Figure 4. Example absorption data taken (a) at 1 kHz on 9/2002, (b) at 4 kHz on 9/2004.

5.0 Personnel

Individual researchers partially or fully supported by the program during the reporting period are listed below. All of the work has been carried out in the High Temperature Gasdynamics Laboratory, at Stanford University, under the direction and supervision of Professor R.K. Hanson.

Dr. Jay B. Jeffries, Senior Research Engineer
Jonathan T.C. Liu, Graduate Research Assistant
Jon Koch, Graduate Research Assistant
Mathew A. Oehlschlaeger, Graduate Research Assistant
Ma Lin, Graduate Research Assistant
Tonghun Lee, Graduate Research Assistant
David Rothamer, Graduate Research Assistant
Gregory Rieker, Graduate Research Assistant

6.0 AFOSR-Sponsored Publications:

6.1 Refereed Publications

1. J.D. Koch, W. Koban, C. Schulz, R.K. Hanson, "Rayleigh-Calibrated Fluorescence Quantum Yield Measurements of Acetone and 3-Pentanone," *Applied Optics* **43**, 5901-5910 (2004).
2. W. Koban, J.D. Koch, R.K. Hanson, C. Schulz, "Absorption and Fluorescence of Toluene Vapor at Elevated Temperatures," *Physical Chemistry Chemical Physics* **6**, 2940-2945 (2004).
3. W. Koban, J. Koch, V. Sick, N. Wermuth, R.K. Hanson, and C. Schulz, "Predicting LIF Signal Strength for Toluene and 3-Pentanone under Transient Temperature and Pressure Conditions," *Proceedings Combustion Institute* **30**, 1545-1553 (2005).
4. W. Koban, J.D. Koch, R.K. Hanson, C. Schulz, "Toluene LIF at Elevated Temperatures: Implications for Fuel-Air Ratio Measurements," *Applied Physics B* **80**, 147-150 (2005).
5. W. Koban, J.D. Koch, R.K. Hanson, C. Schulz, "Oxygen Quenching of Toluene Fluorescence at Elevated Temperatures," *Applied Physics B* **80**, 777-784 (2005).
6. T. Lee, W.G. Bessler, H. Kronmayer, C. Schulz, J.B. Jeffries, "Quantitative temperature measurements in high-pressure flames with multi-line NO-LIF thermometry," *Applied Optics* (2005) in press.
7. J.T.C. Liu, J.B. Jeffries and R.K. Hanson, "Large-Modulation-Depth 2f Spectroscopy with Diode Lasers for Rapid Temperature and Species Measurements in Gases with Blended and Broadened Spectra," *Applied Optics*, **43**, 6500-6509 (2004).
8. H. Li, G.B. Rieker, X. Liu, J.B. Jeffries, and R.K. Hanson, "Extension of Wavelength Modulation Spectroscopy to Large Modulation Depth for Diode Laser Absorption Measurements in High Pressure Gases," *Applied Optics*, submitted June, 2005.
9. J.B. Jeffries, C. Schulz, D.W. Mattison, M.A. Oelschlaeger, W.G. Bessler, T. Lee, D.F. Davidson, and R.K. Hanson, "UV Absorption of CO₂ for Temperature Diagnostics of

Hydrocarbon Combustion Applications,” *Proceedings Combustion Institute* **30**, 1591-1599 (2005).

10. M.A. Oehlschlaeger, D.F. Davidson, J.B. Jeffries, and R.K. Hanson, “Ultraviolet Absorption Cross Sections of Hot Carbon Dioxide,” *Chemical Physics Letters* **399**, 490-495 (2004).
11. M.A. Oehlschlaeger, D.F. Davidson, J.B. Jeffries, “Temperature measurements behind shock waves using ultraviolet laser absorption of carbon dioxide,” *Applied Optics* (2005) in press.
12. J.T.C. Liu, G.B. Rieker, J.B. Jeffries, R.K. Hanson, M.R. Gruber, C.D. Carter, and T. Mathur, “Near-infrared diode laser absorption diagnostics for temperature and water vapor in a scramjet combustor,” *Applied Optics* (2005) in press.
13. T. Lee, W. G. Bessler, C. Schulz, M. Patel, J.B. Jeffries, and R.K. Hanson, “UV Planar Laser Induced Fluorescence Imaging of Hot Carbon Dioxide in a High-Pressure Flame,” *Applied Physics B*, **79**, 427-430 (2004).
14. D.W. Mattision, M.A. Oehlschlaeger, C.I. Morris, Z.C. Owens, E.A. Barbour, J.B. Jeffries, and R.K. Hanson, “Evaluation of Pulse Detonation Engine Modeling using Laser-Based Temperature and OH Concentration Measurements,” *Proceedings Combustion Institute* **30**, 2799-2807 (2005).
15. M.A. Oehlschlaeger, D.F. Davidson, J.B. Jeffries, and R.K. Hanson, “Carbon Dioxide Thermal Decomposition: Observation of Incubation,” *Zeitschrift für Physikalische Chemie*, **219** 555-567 (2005).
16. W. Juchmann, J. Luque, and J.B. Jeffries, “Two-Photon Laser-Induced Fluorescence of Atomic Hydrogen in a Diamond Depositing dc-Arcjet,” *Applied Optics* (2005) in press.
17. X. Liu, X. Zhou, J. B. Jeffries and R. K. Hanson, Experimental Study of H₂O Spectroscopic Parameters in the Near-IR (6940-7440 cm⁻¹) for Gas Sensing Applications at Elevated Temperature,” *J. Quantitative Spectroscopy Radiative Transfer*, submitted July, 2005.

6.2 Ph.D. Theses

1. J.T.C. Liu, “Near-Infrared Diode Laser Absorption Diagnostics for Temperature and Species in Engines,” Ph.D. Thesis, Department of Mechanical Engineering, Stanford, CA, October, 2004, ThermoSciences Division Report 154, <http://navier.stanford.edu/tsd/TSD-154.pdf>.
2. Jon Koch, “Fuel Tracer Photophysics for Quantitative Planar Laser-Induced Fluorescence,” Ph.D. Thesis, Department of Mechanical Engineering, Stanford, CA, May, 2005, ThermoSciences Division Report 159, <http://navier.stanford.edu/tsd/TSD-159.pdf>.
3. M. A. Oehlschlaeger, “Shock Tube Studies of Thermal Decomposition Reactions using Ultraviolet Laser Absorption Spectroscopy,” Ph.D. Thesis, Department of Mechanical Engineering, Stanford, CA, June, 2005, ThermoSciences Division Report 160, <http://navier.stanford.edu/tsd/TSD-160.pdf>.

7.0 Interactions/Transitions

7.1 Participation/presentations at meetings, conferences, seminars

1. R.K. Hanson and J.B. Jeffries, "Advances in Laser-Based Sensors for Propulsion Systems, 24th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, July 2004, Portland, OR, paper AIAA-2004-2476.
2. Xiang Liu, Xin Zhou, Jay B. Jeffries and Ronald K. Hanson, "Experimental Study of H₂O Spectroscopic Parameters in the Near-IR, " 43rd AIAA Aerospace Sciences Meeting and Exhibit, January, 2005, Reno, NV, paper AIAA-2005-0829.
3. Daniel W. Mattison, Jonathan T.C. Liu, Gregory B. Rieker, Jay B. Jeffries, and Ronald K. Hanson Diode Laser Sensors for Internal Combustion and Aeropropulsion Engine Applications, Thermosciences Division Industrial Affiliates, Stanford University, February, 2005.
4. R.K.Hanson and J.B.Jeffries, "Advances in Laser-based Sensors for Combustion Research," Sixth Symposium on Smart Control of Turbulence, Tokyo, Japan, March, 2005; invited plenary lecture.
5. R.K. Hanson, "Diode Laser Sensors for Combustion and Propulsion Applications," Tokyo Institute of Technology, March, 2005.
6. T. Lee, W.G. Bessler, H. Kronmayer, C.Schulz, J.B. Jeffries, R.K. Hanson, Quantitative Temperature Measurements in High-Pressure Flames with Multi-Line Nitric Oxide (NO)-LIF Thermometry, Joint Meeting of the US Sections of the Combustion Institute, Philadelphia, PA, March, 2005.
7. M. A. Oehlschlaeger, "Shock Tube Studies of Thermal Decomposition Reactions using Ultraviolet Laser Absorption Spectroscopy," Combustion Research Facility, Sandia National Laboratory, Livermore, CA, May, 2005.
8. J. Koch, "Fuel Tracer Photophysics for Quantitative Planar Laser-Induced Fluorescence," Marquette University, April, 2005.
9. R.K. Hanson, J.B. Jeffries, M.G. Allen, "Tunable Diode Laser Absorption Sensor Applications to Aeropropulsion Testing," NATO RSM-017 Applied Vehicle Technology Panel Specialists' Meeting on Recent Developments in Non-Intrusive Measurement Technology, Budapest, Hungary, April, 2005; invited plenary lecture.
10. Gruber, M., Eklund, D., Mathur, T., and Jeffries, J., "In-Stream Measurements at the Exit of Dual-Mode Hydrocarbon-Fueled Scramjet Combustors," JANNAF 40th Combustion Subcommittee, 28th Airbreathing Propulsion Subcommittee, 22nd Propulsion Systems Hazards Subcommittee, and 4th Modeling and Simulation Subcommittee Joint Meeting, June 2005.
11. A.E. Klingbeil, J.B. Jeffries, R.K. Hanson, C. Brophy, and J. Sinibaldi, "Mid-IR Laser Absorption Measurements of Ethylene in a Pulsed Detonation Engine," 41st Joint Propulsion Conf., Tucson, AZ, July, 2005, paper AIAA-2005-4375.

12. G.B. Rieker, J.T.C. Liu, J.B. Jeffries, R.K. Hanson, T. Mathur, M.R. Gruber, and C. Carter, "Diode Laser Sensor for Gas Temperature and H₂O Concentration in a Scramjet Combustor Using Wavelength Modulation Spectroscopy," 41st Joint Propulsion Conf., Tucson, AZ, July, 2005, paper AIAA-2005-3710.

7.2 Interactions and Collaboration with AFRL

A measurement campaign was conducted to perform diode laser sensing measurements in the scramjet combustor test facility at AFRL at Wright Patterson AFB, OH. This was the second set of measurements conducted in collaboration with Dr. Mark Gruber and Dr. Campbell Carter of AFRL. The improved optical engineering used to match this sensor with the optical access in the test facility enabled major improvement in signal to noise (see Fig. 4 above). The results have been presented in a journal paper (Refereed publications #14), a presentation at the AIAA Joint Propulsion Conference by Stanford student Greg Rieker (Presentations at Meetings #12), and some of the data were included in a presentation at the June 2005 JANNAF meeting by Dr. Gruber of AFRL (Presentations at Meetings #10). A third measurement campaign in our program to transfer this measurement technology to AFRL is planned.

Dr. Jeffries of Stanford participated in a workshop in May 2005 at AFRL organized by Barry Kiel to facilitate diagnostic measurements on augmented jet engines. A joint project with Pratt and Whitney (Jeff Lovett), AEDC, AFRL, and ISSI is envisioned.

7.3 Transitions

Performer: R. K. Hanson, Stanford University (650-723-1745)

Customer: Dr. Michael Winter, Pratt and Whitney, East Hartford (860-565-9007)

AFOSR Result: Tunable diode laser diagnostics

Application: Development of new sensor for air mass flux for full-scale aero-engine testing; Stanford University students performed successful proof-of-concept test measurements on a P&W 6000 engine in July 2005.

Performer: R. K. Hanson, Stanford University (650-723-1745)

Customer: Dr. Douglas Baer, Los Gatos Research (650 965 7778)

AFOSR Result: High Pressure Laser-Induced Fluorescence of NO

Application: Gas turbine combustor ground test measurements of NO spatial distributions

Performer: R. K. Hanson, Stanford University (650-723-1745)

Customer: Dr. Andrew Sappey, Zolo Technology, (303-604-5804)

AFOSR Result: Tunable diode laser diagnostics

Application: Ground test of augmented jet engines and scramjet vehicle health monitoring systems

Performer: R. K. Hanson, Stanford University (650-723-1745)

Customer: Dr. Anthony Dean, General Electric Global Research Center (518-387-6478)

AFOSR Result: Mid-IR laser absorption of fuel

Application: PDE fuel cycle optimization and the measurement of unburned fuel

8. New discoveries, inventions, patent disclosures

None

9. Honors/Awards

Professor Ronald K. Hanson was awarded the AIAA Propellants and Combustion Award during the past year.

Lifetime awards of Professor Ronald K. Hanson:

- | | |
|------|--|
| 1990 | Fellow, Optical Society of America (OSA)
Woodard Chair of Mechanical Engineering, Stanford University |
| 1996 | Aerodynamic Measurement Technology award from the AIAA (first recipient) |
| 1997 | Fellow, American Institute of Aeronautics and Astronautics (AIAA) |
| 2001 | Elected to the National Academy of Engineering |
| 2002 | Silver Medal of the Combustion Institute |
| 2004 | Fellow, American Society of Mechanical Engineers |
| 2005 | Propellants and Combustion award from the AIAA |

10. Principal Investigator Annual Data Spreadsheet

PI Name	R. K. Hanson
Number of years supported by your program (If more than 6, comment on degree of evolution/change in program goals) (Newer PMs may need assistance from PK on this.)	28; The central thrust of the program has been to investigate and develop new laser-based diagnostics for air-breathing propulsion. The diagnostic strategies under study have evolved significantly over this period. In the early phase of the program, emphasis was placed on lead-salt diode lasers for absorption and pulsed tunable lasers for planar fluorescence imaging. Current lasers utilize communications grade near-IR diode lasers which can be multiplexed to allow many simultaneous wavelengths; and optical parametric oscillators are now used to provide IR excitation. The result over time has been a continued evolution of new diagnostic strategies.
Year in which PI received PhD	1968
Recognition and honors: Major Prizes, Awards, recognition (e.g. PECASE, Nobel, other prize/recognition include technical field if appropriate)	AIAA Award for Aerodynamic Measurement Technology (first recipient), Woodard Chair of Mechanical Engineering at Stanford Univ., Silver Medal of the Combustion Institute AIAA Award for Propellants and Combustion
US Academy of Sciences and Engineering	NAE (National Academy of Engineering)
Fellow of Professional Society (which)	OSA (Optical Society of America) AIAA (American Institute of Aeronautics and Astronautics) ASME (American Society of Mechanical Engineers)
Professional Society offices held, and Editorships, if known to PM	Chair, Western States Section of Combustion Institute Program Chair, 2004 International Symposium on Combustion Associate Editor: J. Quant. Spectroscopy and Rad. Transfer; Int. J. Chemical Kinetics; Comb. Sci. and Technology; Int. J. of Shock Waves; Prog. In Energy and Combustion Science
Publications in FY04 resulting from AFOSR managed effort	17 refereed publications, 3 Ph.D theses, and 12 meeting presentations
Sum of FTE years (FTE=Full Time Equivalent, i.e. "person years") supported in FY04 by AFOSR managed effort	5

Number of students and
post Docs supported by
AFOSR managed effort
(enter as P=Post Doc, G=
Graduate and U=
undergraduate students)

Post Docs	0.25
Graduate Students	4
Undergraduate Students	0